

Probing physics beyond the standard model from lepton sector

J. Hisano^aICRR] Institute of Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan

^bKEK]Theory Group, KEK, Tsukuba 305-0801, Japan

^a[

^b[

In this review we discuss physics of the lepton sector, the anomalous dipole moment of muon, the charged lepton-flavor violation, and the electric dipole moments of charged leptons, from viewpoints of the minimal supersymmetric standard model and the extensions.

1. Introduction

The Standard Model (SM) is the most successful model to explain physics below the weak scale. The recent results for $\sin 2\beta$ or $\sin 2\phi_1$ by Belle [1] and Babar [2] are converging, and they are consistent with the Kobayashi-Maskawa mechanism [3]. Also, the precision measurements of the electroweak parameters suggest the light SM Higgs boson such as $m_h \lesssim 196\text{GeV}$ (95%CL) [4]. Now we are waiting for signature of physics beyond the SM.

We have the clue for the physics beyond the SM in the neutrino oscillation experiment results. The atmospheric neutrino result by the superKamiokande experiment is established [5]. The combined result of the superKamiokande [6] and SNO [7] experiments shows a strong evidence for the appearance of ν_μ or ν_τ in the solar neutrino. At present, the large-angle MSW solution is the most favored, which will be checked by the Kamland experiment soon [8]. These neutrino oscillation results can be explained by introduction of small neutrino masses.

Introduction of small neutrino masses gives us a new scenery for physics beyond the SM. While the promising candidate for origin of the small neutrino masses is the see-saw mechanism [9] by introduction of the right-handed neutrinos, the atmospheric neutrino result implies that the right-handed neutrino mass should be smaller than $\sim 10^{-15}\text{GeV}$, which is much smaller than the Planck

scale. This is a good motivation for introduction of Supersymmetry (SUSY). A quadratically-divergent contribution to the Higgs boson mass proportional to the right-handed neutrino masses should be canceled even if the correction proportional to the Planck mass is vanishing by some mysterious physics.

Nowadays, the minimal supersymmetric standard model (MSSM) is one the most promising extension of standard model (SM), and many experiments are searching for the possible evidence of the low-energy supersymmetry. In this review we discuss the possibilities in physics of charged lepton, paying attention to the dipole-moment operators;

$$\mathcal{L} = e \frac{m_{l_j}}{2} \bar{l}_i \sigma_{\mu\nu} F^{\mu\nu} (L_{ij} P_L + R_{ij} P_R) l_j \quad (1)$$

where $P_{R/L} = (1 \pm \gamma_5)/2$, and i, j are for the generation. These operators are sensitive to physics beyond the SM. The real diagonal parts of L_{ij} and R_{ij} contributes to the anomalous magnetic moments of charged leptons, $a_{l_i} (\equiv (g_{l_i} - 2)/2) = m_{l_i}^2 (R_{ii} + L_{ii})$. They are sensitive to structure of the Higgs sector, since the operator (1) is violating the lepton chiral symmetry and the $SU(2)_L \times U(1)_Y$ symmetry. In fact, the MSSM may predict the larger correction to it than the electroweak correction since the MSSM has two doublet Higgs bosons.

If non-vanishing L_{ij} or R_{ij} ($i \neq j$) exists, the charged lepton-flavor violating (LFV) processes, such as $\mu \rightarrow e\gamma$, are predicted; $Br(\mu \rightarrow e\gamma) \propto$

($|R_{\mu e}|^2 + |L_{\mu e}|^2$). Now we know from the neutrino oscillation results that the lepton-flavor symmetry is not exact in nature, and the problem is how large is the charged LFV. The small neutrino masses themselves, expected from the neutrino oscillation results, cannot give any prediction for the charged LFV processes accessible in near future. In the MSSM, the charged LFV is supplied by the SUSY breaking masses of sleptons, and the magnitude depends on the origin of the SUSY breaking and interaction beyond the MSSM, such as in see-saw mechanism or the supersymmetric grand unified models (SUSY GUTs).

When diagonal parts of L_{ij} and/or R_{ij} have imaginary part, CP is violating and the electric dipole moments (EDM) are predicted; $d_{l_i} = em_{l_i} \text{Im}(R_{ii} - L_{ii})$. The EDMs are also supplied by the SUSY breaking slepton masses in the MSSM.

We organize this review as follows. In the next section we summarize the current status of the muon ($g - 2$). In section 2 we discuss dependence of the charged LFV processes on the SUSY breaking models, and show the branching ratios of the charged LFV processes in the supersymmetric see-saw model, using the neutrino oscillation data. Section 3 is for the EDMs of charged leptons. Section 4 is summary.

2. Muon anomalous magnetic moment

The latest result for the anomalous magnetic moment of muon (BNL'98&'99+CERN'77 [10]) is $a_\mu^{\text{exp}} = (116\,592\,023 \pm 151) \times 10^{-11}$, while the SM prediction is $a_\mu^{\text{SM}} = (116\,592\,768 \pm 65) \times 10^{-11}$. The contents of the SM contribution are listed in Table 1. The deviation of the measurement from the SM prediction is $a_\mu^{\text{NP}} (\equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}}) = 255 \pm 164 \times 10^{-11}$, and it is 1.6σ away. At present the significance of the deviation is small. The experimental error is expected to be improved by a factor 2 in BNL'00 data, and the ultimate goal may be $\sim 40 \times 10^{-11}$.

Before going to the SUSY contribution to the muon $g - 2$, we review the error in the SM prediction. The largest ambiguities in the SM prediction come from the leading hadronic vacuum polarization contribution $a_\mu^{\text{Had}}(\text{VP1})$ and the hadronic light-by-light (LbyL) scattering contri-

Table 1

The SM contribution to the muon $g - 2$.

	($\times 10^{11}$)	
a_μ^{QED}	116 584 705.7(2.9)	[11]
$a_\mu^{\text{Had}}(\text{VP1})$	6 924(62)	[12]
$a_\mu^{\text{Had}}(\text{VP2})$	-100(6)	[13]
$a_\mu^{\text{Had}}(\text{LbyL})$	86(19)	[14] [15]
$a_\mu^{\text{EW}}(1 \text{ loop})$	195	[16]
$a_\mu^{\text{EW}}(2 \text{ loop})$	-43(4)	[17]
a_μ^{SM}	116 591 768(65)	

bution $a_\mu^{\text{Had}}(\text{LbyL})$. The $a_\mu^{\text{Had}}(\text{VP1})$ in Table 1 is derived by M. Davier and A. Hocker [12] from the e^+e^- hadronic cross section and the hadronic τ decay data, including perturbative QCD calculation in the high q^2 part.¹ This estimation will be further improved by high quality data for the e^+e^- hadronic cross section by CMD2 in Novosibirsk [19], KLOE in Fascati [20], and BES in Beijing [21]. The Babar may contribute to it by measurement via the initial state radiation of hard photon [22]. The CLEO and LEP data for the tau decay are also important.

On the other hand, the estimate of the LbyL scattering contribution relies on the model calculation. The LbyL contribution comes from three type diagrams in Fig. 1, and the value in Table 1 is the average value for the latest results of Refs. [14] and [15];

$$a_\mu^{\text{Had}}(\text{LbyL}) = (89.6 \pm 15.4) \times 10^{-11} \text{ [14]}, \quad (2)$$

$$a_\mu^{\text{Had}}(\text{LbyL}) = (83 \pm 32) \times 10^{-11} \text{ [15]}. \quad (3)$$

The dominant contribution in $a_\mu^{\text{Had}}(\text{LbyL})$ comes from the pion-pole diagram. This diagram was reevaluated by several groups [23][14][15], and the sign problem has been fixed now. However, still they rely on the model calculation since the diagram is divergent. They are based on the chiral perturbation or the ENJL model. The vector-meson dominance is assumed and the phenomenological parametrization of the pion form factor $\pi\gamma^*\gamma^*$ is introduced in order to regularize the divergence.

¹See also Refs. [18] for discussion of the estimation of the leading hadronic vacuum polarization contribution.

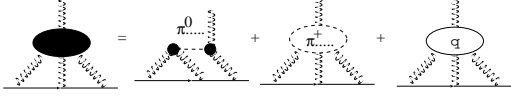


Figure 1. The light-by-light scattering contributions to the muon $g - 2$.

In Ref. [24] the pion-pole contribution is evaluated in a model-dependent way, based on the chiral perturbation theory. The result is following;

$$a_{\mu}^{\text{Had}}(\text{LbyL})|_{\pi^0 \text{ pole}} = \frac{3}{16\pi^2} \left(\frac{\alpha}{\pi}\right)^3 \left(\frac{m_{\mu}}{F_{\pi}}\right)^2 \times \left\{ \log^2 \frac{\Lambda}{m_{\mu}} + \left(\frac{1}{6}\chi - 0.17\right) \log \frac{\Lambda}{m_{\mu}} + \tilde{C} \right\},$$

where Λ is the ultraviolet cutoff ($\Lambda \sim 4\pi F_{\pi}$). The largest term proportional to $\log^2 \Lambda/m_{\mu}$ is fixed by the gauge invariance and chiral anomaly. χ is a counter term to regularize the two-loop diagram. While it can be determined by the leptonic decay of the pseudoscalar mesons, the sensitivity is low at present. Furthermore, \tilde{C} , which is a piece not enhanced by log, cannot be evaluated without explicit models. The uncertainty due to \tilde{C} is $\delta a_{\mu} = 31 \times 10^{-11} \tilde{C}$.

While the model-dependent calculations (2) and (3) seem to be converged, we do not have a strategy to derive the pion-pole contribution precisely enough in a model-dependent way. Also, we have a subtle problem in the light-by-light contribution, whether the inclusion of the quark loop is double-counting or not. Thus, the calculation of the light-by-light contribution on base of QCD is strongly desired.

If the hadronic contribution is well-controlled, the muon $g - 2$ is so sensitive to physics beyond the SM [25], as mentioned in Introduction. Before closing this section, we discuss it from a viewpoint of the MSSM. The nature of two Higgs doublet model in the MSSM can enhance the contribution, and the contribution proportional to $\tan \beta$

[26], which comes from Fig. (2), is given as

$$a_{\mu}^{\text{SUSY}} \simeq \frac{5\alpha_2 + \alpha_Y}{48\pi} \frac{m_{\mu}^2}{m_{\tilde{S}}^2} \tan \beta \simeq 1.3 \times 10^{-9} \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^2 \tan \beta.$$

Here, all relevant SUSY breaking parameters are assumed to be common to m_S . Thus, it may be larger than the electroweak correction in the SM and the deviation from the SM in the MSSM may reach to 10^{-8} .

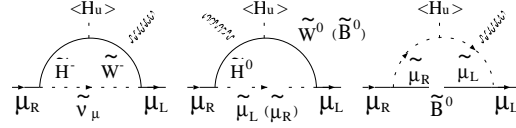


Figure 2. The contributions in the MSSM to the muon $g - 2$, which are enhanced by $\tan \beta$.

If the sizable deviation is observed, it will supply a big impact on the model building and the phenomenology of the MSSM. After “observation” of 2.6σ deviation of the muon $g - 2$, there were so many activities for it. Here we summarize them briefly.

First is for the mass spectrum of the SUSY particles in the MSSM. If the deviation is observed, relatively lighter slepton and chargino or larger $\tan \beta$ will be favored [27][28]. Especially, when the Higgs mass constraint is included, the SUSY particle spectrum is more constraint, since it prefers to the large stop mass and/or large $\tan \beta$ [29]. In the decoupling solution for the FCNC problem [30], the first and second generation sfermions are much heavier than the weak scale. In these models, even if the slepton mixing between the second and third generations is introduced, the deviation of the muon $g - 2$ can reach to 10^{-9} at most [31].

Second is related to sign of the Higgsino mass parameter μ . The muon $g - 2$ contribution in

the MSSM is proportional to μM_2 in the broad parameter space. Here M_2 is the $SU(2)_L$ gaugino mass. Now $b \rightarrow s\gamma$ favors $\mu A_t > 0$, where A_t is the \tilde{t}_L - \tilde{t}_R -Higgs trilinear coupling. If the SUSY breaking in the MSSM comes from physics at high energy scale, such as the minimal supergravity model, $A_t \sim M_3$ where M_3 is the $SU(3)_C$ gaugino mass. If sign of the two gaugino masses is required to have the same sign, the anomaly mediated SUSY breaking model [32] will be disfavored [27]. The consistency of the muon $g-2$ and the Yukawa unification ($Y_t = Y_b = Y_\tau$) at the GUT scale is also interesting since the Yukawa unification favors $\mu M_3 < 0$ [33].

Third is the $\tan\beta$ enhanced processes. If the muon $g-2$ deviation is observed, it will give normalizations of the processes induced by dipole operators. Especially, the LFV processes, such as $\mu \rightarrow e\gamma$, have a direct relation to it [34]. The processes generated by the Yukawa coupling may be also enhanced. For example, the counting rate of the neutralino dark matter would be enhanced [35].

3. Lepton-flavor violation in the charged-lepton sector

While the lepton-flavor violation is observed in the neutrino oscillation experiments, this does not mean sizable LFV processes in the charged-lepton sector exist. The charged LFV processes induced by the small neutrino masses, expected from the neutrino oscillation results, are suppressed by the GIM mechanism, as $Br(\mu \rightarrow e\gamma) \lesssim 10^{-48} (m_\nu/1\text{eV})^4$, even if the neutrino mixing is maximal. On the other hand, if the SM is supersymmetrized, the situation is changed. The SUSY breaking slepton masses are not necessarily aligned to the lepton masses, and it may lead to sizable lepton-flavor violating.

Let us assume that $(m_L^2)_{12}$ in the left-handed slepton mass matrix is non-vanishing. In this case, $\mu \rightarrow e\gamma$ is generated by diagrams in Fig. (3), and the approximate formula is given as $Br(\mu \rightarrow e\gamma) \simeq 3 \times 10^{-5} (a_\mu^{\text{SUSY}}/10^{-9})^2 ((m_L^2)_{12}/m_S^2)^2$ [34]. The diagrams in Fig (3) are so similar to the diagrams in Fig. (2) contributing to the muon $g-2$, and the muon $g-2$ gives the normalization of the

branching ratio of $\mu \rightarrow e\gamma$.

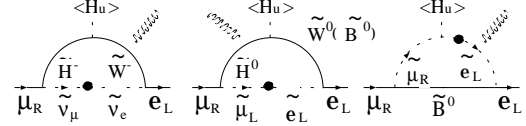


Figure 3. The contributions in the MSSM to the $\mu \rightarrow e\gamma$, which are enhanced by $\tan\beta$. Here, it is assumed that the left-handed sleptons have the LFV masses.

In Table 2 we summarize the current experimental bounds to the charged LFV processes, the sensitivities in the present activities, and prospects in the future experiments such as the PRISM project [45] and the front ends of neutrino factories under consideration at CERN [40]. The charged LFV processes are radiative-induced in the MSSM as far as the R party is not broken. Thus, the branching ratio of $\mu \rightarrow 3e$ and the μ - e conversion rate in nuclei are approximately given as $Br(\mu \rightarrow 3e)/Br(\mu \rightarrow e\gamma) \simeq 7 \times 10^{-3}$ and $R(\mu^- \text{Ti(Al)} \rightarrow e^- \text{Ti(Al)})/Br(\mu \rightarrow e\gamma) \simeq 5(3) \times 10^{-3}$. (See the detailed calculation of the μ - e conversion rate in nuclei is given in Refs. [46].) From these simple formulas, the naive current bound on $(m_L^2)_{12}/m_S^2$ is $\lesssim 6 \times 10^{-4} (\delta a_\mu^{\text{SUSY}}/10^{-9})^{-1}$, and PSI and MECO/BNL (PRISM and NuFACT) may reach to $\sim 10^{-5} (10^{-6})$. These experiments are stringent tests of the lepton-flavor symmetry in the MSSM.

The charged LFV in the MSSM depends on the origin of the SUSY breaking term in the MSSM and the interaction of physics beyond the MSSM. The SUSY breaking model is classified to two types by degeneracy or non-degeneracy of the sfermion masses. The later may predict the large LFV rates and sometimes the broad parameter region has been excluded already. Here, we will concentrate on the SUSY breaking models where the degeneracy of the sfermion masses is predicted by assuming the hidden sector, such

Table 2

Current experimental bounds to the charged LFV processes, the sensitivities in the present activities, and prospects in the future experiments.

	Current bound	Present Activities	Future
$\tau \rightarrow \mu \gamma$	1.0×10^{-6} [36]	$\sim 10^{-7}$ (Belle/KEK) [37]	$10^{-(8-9)}$ [37]
$\mu \rightarrow e \gamma$	1.2×10^{-11} [38]	2×10^{-14} (PSI) [39]	10^{-15} [40]
$\mu \rightarrow 3e$	1.0×10^{-12} [41]		$10^{-(15-16)}$ [40]
$\mu^- N \rightarrow e^- N$	6.1×10^{-13} [42]	10^{-14} for Ti (SINDRUM II) [43] 5×10^{-17} for Al (MECO/BNL) [44]	10^{-18} [40] [45]

as the gravity- [47], gauge- [48], anomaly- [32], gaugino-mediation [49] models.

The magnitude of the charged LFV processes in these models depends on the scale of the SUSY breaking mediation (M_M) and the scale of the physics with LFV interaction (M_{LFV}). The well-motivated candidates for the physics with LFV interaction are the SUSY GUTs and the see-saw mechanism. If $M_M \gtrsim M_{LFV}$, such as in the gravity-mediation model, the LFV slepton masses are radiatively generated by the LFV interaction and they depend on $\log M_M/M_{LFV}$. The LFV processes may have observable rates in this case [50][51][52].

In the gaugino-mediation model, where M_M is the reduced Planck scale or the GUT scale, the scalar masses at M_M are vanishing, and they are generated through the gaugino loops. The LFV slepton masses are induced at higher order and suppressed. However, the suppression of the LFV processes is at most a factor 10. In Fig. (4) the dependence of $Br(\mu \rightarrow e \gamma)$ on the universal scalar mass m_0 in the gravity-mediation model. The two lines are for M_M the GUT scale or the reduced Planck scale. Here, the the $SU(2)_L$ gaugino mass M_2 is 200GeV, and the supersymmetric see-saw model is assumed. See Ref. [34] for the other input parameters. The branching ratio is maximum at $M_2 \sim m_0$. When m_0 is zero (the gaugino-mediation limit), the branching ratio is suppressed, however it is only a factor 10.

When $M_M \lesssim M_{LFV}$, such as in the low-energy gauge-mediation model, the radiative correction is suppressed by a power of M_M/M_{LFV} , and the effect tends to be invisible. The anomaly-mediation model is exceptional. While M_M is the gravitational scale, the SUSY breaking pa-

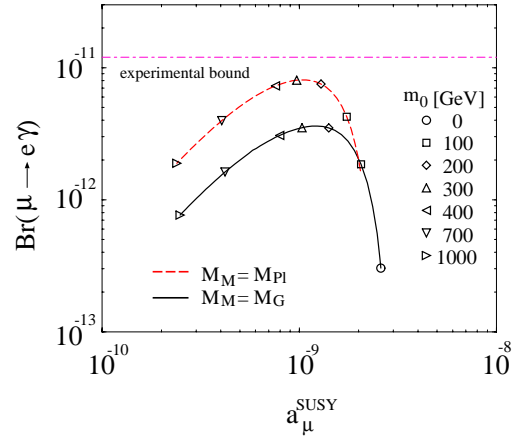


Figure 4. Dependence of $Br(\mu \rightarrow e \gamma)$ on the universal scalar mass m_0 in the supersymmetric seesaw model, assuming the gravity-mediation model. Here, the $SU(2)_L$ gaugino mass M_2 is 200GeV.

rameters are determined by only the particle contents and interactions in the MSSM in the original anomaly-mediation model (the UV insensitivity), and the LFV slepton masses are suppressed. On the other hand, the model has the problem of tachyonic sleptons. Then, the LFV slepton masses in this model depends on how to care of the problem. For example, in the minimal anomaly-mediation model [53], where the universal scalar mass m_0 is added to the anomaly-mediation contribution, the LFV slepton masses are generated and proportional to m_0^2 .

Next, we will discuss the charged LFV processes in the supersymmetric see-saw model using the the neutrino oscillation results. We assume the gravity-mediation model. The atmospheric neutrino result suggests the large mixing of left-handed stau and smuon, and it may imply the large branching ratio of $\tau \rightarrow \mu\gamma$. In Fig. (5) we present $Br(\tau \rightarrow \mu\gamma)$ in this model. Here, we use $m_{\nu_\tau}^2 = 2 \times 10^{-3} \text{eV}^2$ and $U_{23} = 1/\sqrt{2}$, and assume that the large mixing comes from the neutrino Yukawa coupling and that the Yukawa unification of the tau-neutrino and top-quark Yukawa couplings is imposed at the reduced Planck scale. These assumptions make $Br(\tau \rightarrow \mu\gamma)$ enhanced. For the SUSY breaking parameters, we take $m_0 < 500 \text{GeV}$, the $U(1)_Y$ gaugino mass $< 500 \text{GeV}$, and the universal A parameter A_0 zero. While a parameter region is excluded, the branching ratio tends to be smaller than the reach of the KEK Belle. If the large deviation from the SM prediction in the muon $g - 2$, such as $\sim 10^{-9}$, is observed, the branching ratio may be larger than 10^{-9} .

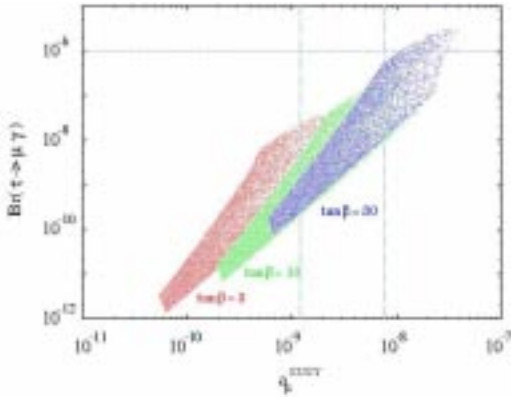


Figure 5. $Br(\tau \rightarrow \mu\gamma)$ in the supersymmetric see-saw model, assuming the gravity-mediation model. Here, we use the atmospheric neutrino result. The horizontal line is the MSSM contribution to the muon $g - 2$.

Now the large-angle MSW solution is the most favored in the solar neutrino problem, and this may lead to the large branching ratio of $\mu \rightarrow e\gamma$. In Fig. (6) we show $\mu \rightarrow e\gamma$, using the atmospheric neutrino result and the large-angle MSW solution; $m_{\nu_\mu}^2 = 7.5 \times 10^{-5} \text{eV}^2$ and $U_{12} = 1/\sqrt{2}$. Here we take $m_{\nu_e} = 0$ and assume the canonical generational structure for the right-handed neutrino masses. For the SUSY breaking parameters, the universal gaugino mass $M_{1/2} = 200 \text{GeV}$, $m_0 = 200 \text{GeV}$, and $A_0 = 200 \text{GeV}$. The horizontal line is for the right-handed tau neutrino mass M_{N_τ} . A broad region has been excluded already, and the future experiments may cover almost the region above $M_{N_\tau} \gtrsim 10^{11} \text{GeV}$. If $M_{N_\tau} \lesssim \mathcal{O}(10^{11}) \text{GeV}$, the Dirac mass for the tau neutrino is smaller than $\mathcal{O}(1) \text{GeV}$, which is much smaller than the top quark mass.

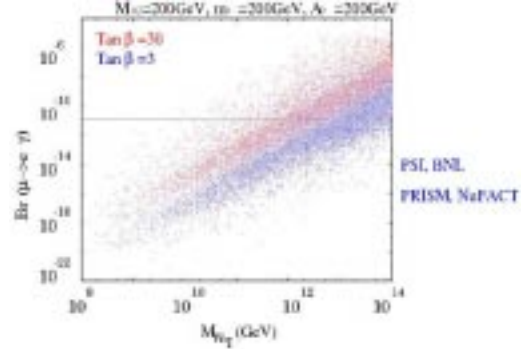


Figure 6. $Br(\mu \rightarrow e\gamma)$ in the supersymmetric see-saw model, using the atmospheric neutrino result and the large-angle MSW solution. We assume the gravity-mediation model.

In this section we discussed the charged LFV. After the SUSY particles are discovered at LHC or lepton colliders, the LFV slepton decay is important [54]. The e^+e^- linear collider and muon collider have sensitivity for the $\tilde{\tau}$ - $\tilde{\mu}$ mixing beyond the current proposed $\tau \rightarrow \mu\gamma$ search.

4. EDMs

In this section we discuss the EDMs of charged leptons. The current experimental bounds and the sensitivities of the future experiments are listed in Table 3. While the EDMs are suppressed in the SM as $d_e(d_\mu) < 10^{-40}(10^{-38})e$ cm, they are sensitive to the MSSM. The relative phases of the F -term SUSY breaking parameters, the A and B terms and the gaugino masses, contribute to the EDMs. In this section, we assume for simplicity that the sfermion masses are flavor-independent and the CP-violating phases of the SUSY breaking parameters are zero at the SUSY-breaking mediation scale, and consider the EDMs radiatively-induced in physics beyond the MSSM.

In the minimal SUSY SU(5) GUT, the predicted EDMs are very small. The quark and lepton masses are given by the up-type and down-type quark Yukawa couplings at the GUT scale. As the result, the EDMs of electron and muon are proportional to a Jaroskog invariant, $\sim f_b^2 f_c^2 f_t^4 \text{Im}[V_{11} V_{12}^* V_{22} V_{21}^*]$, where V is the CKM matrix at the GUT scale. This situation is similar to the SM. Thus, the EDMs are suppressed so much.

We know that the minimal SUSY SU(5) GUT cannot explain the quark and lepton masses for the first and second generations, and the extension is needed. Also, it does not have the right-handed neutrinos. These extension may change the prediction for the EDM drastically [51]. Let us consider that the SUSY SU(5) GUT with the right-handed neutrinos. In this case, the EDM of electron (muon) may be proportional to a Jaroskog invariant, $\sim f_{\nu_\tau}^2 f_t^2 \text{Im}[V_{31(2)} V_{33}^* U_{1(2)3} U_{33}^*]$. Here, we assume for simplicity that the right-handed neutrino masses are degenerate and U is the MNS matrix at the GUT scale. The relative phases between U and V contribute to the EDMs. In Fig. (7) we show the $Br(\mu \rightarrow e\gamma)$ and the EDMs of electron and muon. We assume the maximal CP violating phases. See Ref. [60] for the input parameters in this figure. Since the left-handed and right-handed sleptons get the LFV masses as $(m_L^2)_{ij} \propto U_{i3} U_{j3}^*$ and $(m_E^2)_{ij} \propto V_{3i} V_{3j}^*$, $Br(\mu \rightarrow e\gamma)$ and the EDMs have a strong correlation. From this figure it is found that the

prediction may be accessible in the future experiments, and U_{13} is an important parameter for the electron EDM.

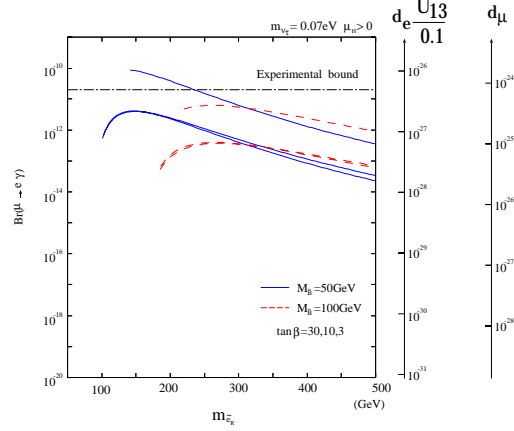


Figure 7. $Br(\mu \rightarrow e\gamma)$ and the EDMs of electron and muon in the SUSY SU(5) GUT with the right-handed neutrinos.

In the supersymmetric see-saw model, if the right-handed neutrino masses are exactly degenerate, the EDMs of charged leptons are also suppressed, similar to the minimal SUSY SU(5) GUT. The non-degeneracy of the right-handed neutrino masses may enhance the EDMs drastically [59], and the muon (electron) EDM can reach to $10^{-26}(10^{-31})e$ cm.

Other CP violating observable in the lepton sector is the T-odd asymmetry in the polarized muon decay to $3e$. While it comes from interference between the photon-penguin diagram and the Z penguin and box diagrams, the photon-penguin diagram tends to be dominant in the $\mu \rightarrow 3e$ process and the T-odd asymmetry is suppressed. In the minimal SUSY SU(5) GUT and the supersymmetric see-saw model the T-odd asymmetry may reach to 10% if the photon-penguin contribution is suppressed [61][62].

Table 3

The current experimental bounds to the electric dipole moments of charged leptons and the prospects in the future experiments.

	Current bound	Present Activities	Future
$d_e (e \text{ cm})$	$1.6 \times 10^{-27} e$ [55]		10^{-33} [56]
$d_\mu (e \text{ cm})$	$(3.7 \pm 3.4) \times 10^{-19}$ [57]	2×10^{-24} (BNL) [58]	10^{-26} [40] [45]

5. Summary

In this review we discuss physics of the lepton sector from viewpoints of the minimal supersymmetric standard and the extensions. While the muon $g - 2$ is sensitive to the MSSM, the understanding of the systematic error in the SM prediction, especially the light-by-light contribution, is very serious when the experimental error is reduced furthermore. The charged LFV processes depends on the SUSY breaking models and the LFV interaction beyond the MSSM. The current neutrino data is encouraging. The interesting future experiments may give suggestion for the model discrimination. The EDMs of charged leptons are sensitive to the extension of the SUSY GUTs, and they may be accessible in the future experiments.

Acknowledgment

JH thanks Prof. S. Ohta for comment on the lattice calculation of the light-by-light contribution to the muon $g - 2$.

REFERENCES

1. K. Trabelsi, talk given in XXXVII Rencontres de Moriond Electroweak Interactions and Unified Theories, Les Arcs, March 9-16-2002, <http://moriond.in2p3.fr/EW/2002/>.
2. G. Raven, talk given in XXXVII Rencontres de Moriond Electroweak Interactions and Unified Theories, Les Arcs, March 9-16, 2002, <http://moriond.in2p3.fr/EW/2002/>.
3. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.
4. The LEP Electroweak Working Group, <http://lepewwg.web.cern.ch/LEPEPWG/>.
5. Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. 81 (1998) 1562.
6. Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. 82 (1999) 1810; Phys. Rev. Lett. 82 (1999) 2430.
7. Q.R. Ahmad *et al.* [SNO Collaboration], Phys. Rev. Lett. 87 (2001) 071301.
8. K. Inoue, talk given in JPS meeting (March 24-27, 2002), <http://www.awa.tohoku.ac.jp/KamLAND>.
9. M. Gell-Mann, P. Ramond and R. Slansky, Proceedings of the Supergravity Stony Brook Workshop, New York, 1979, eds. P. Van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam); T. Yanagida, Proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, Tsukuba, Japan 1979 (edited by A. Sawada and A. Sugamoto, KEK Report No. 79-18, Tsukuba); R. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980) 912.
10. H.N. Brown *et al.* [Muon $g-2$ Collaboration], Phys. Rev. Lett. 86 (2001) 2227.
11. A. Czarnecki and W.J. Marciano, Nucl. Phys. Proc. Suppl. 76 (1999) 245;
12. M. Davier and A. Hocker, Phys. Lett. B 435 (1998) 427.
13. R. Alemany, M. Davier and A. Hocker, Eur. Phys. J. C 2 (1998) 123.
14. M. Hayakawa and T. Kinoshita, hep-ph/0112102.
15. J. Bijnens, E. Pallante and J. Prades, Nucl. Phys. B 626 (2002) 410.
16. K. Fujikawa, B.W. Lee and A.I. Sanda, Phys. Rev. D 6 (1972) 2923; M. Yoshimura and I. Bars, Phys. Rev. D 6 (1972) 374; G. Altarelli, N. Cabibbo and L. Maiani, Phys. Lett. B 40 (1972) 415.
17. A. Czarnecki, B. Krause and W.J. Marciano, Phys. Rev. D 52 (1995) 2619; S. Peris, M. Perrottet and E.de Rafael, Phys. Lett. B 355 (1995) 523.
18. F.J. Yndurain, hep-ph/0102312; S. Narison, Phys. Lett. B 513 (2001) 53 [Erratum-ibid. B

- 526 (2001) 414]; K. Melnikov, Int. J. Mod. Phys. A 16 (2001) 4591; G. Cvetič, T. Lee and I. Schmidt, Phys. Lett. B 520 (2001) 222; W.J. Marciano and B.L. Roberts, hep-ph/0105056.
19. R.R. Akhmetshin *et al.* [CMD-2 Collaboration], hep-ex/9904027; Nucl. Phys. A 675 (2000) 424C.
 20. B. Valeriani, talk given in XXXVII Rencontres de Moriond Electroweak Interactions and Unified Theories, Les Arcs, March 9-16, 2002, <http://moriond.in2p3.fr/EW/2002/>.
 21. H. Hu, talk given in XXXVII Rencontres de Moriond Electroweak Interactions and Unified Theories, Les Arcs, March 9-16, 2002, <http://moriond.in2p3.fr/EW/2002/>.
 22. O. Buchmüller, talk given in XXXVII Rencontres de Moriond Electroweak Interactions and Unified Theories, Les Arcs, March 9-16, 2002, <http://moriond.in2p3.fr/EW/2002/>; E.P. Solodov [BABAR collaboration], in Proceeding of the e^+e^- physics at intermediate energies conference (ed. Diego Bettoni), Conf C010430 (2001) T03.
 23. M. Knecht and A. Nyffeler, hep-ph/0111058; M. Knecht, A. Nyffeler, M. Perrottet and E. De Rafael, Phys. Rev. Lett. 88 (2002) 071802; I. Blokland, A. Czarnecki and K. Melnikov, Phys. Rev. Lett. 88 (2002) 071803.
 24. M. Ramsey-Musolf and M.B. Wise, hep-ph/0201297.
 25. A. Czarnecki and W.J. Marciano, Phys. Rev. D 64, (2001) 013014.
 26. R. Barbieri and L. Maiani, Phys. Lett. B 117 (1982) 203; D.A. Kosower, L.M. Krauss and N. Sakai, Phys. Lett. B 133 (1983) 305; T.C. Yuan, R. Arnowitt, A.H. Chamseddine and P. Nath, Z. Phys. C 26 (1984) 407; C. Arzt, M.B. Einhorn and J. Wudka, Phys. Rev. D 49 (1994) 1370; J.L. Lopez, D.V. Nanopoulos and X. Wang, Phys. Rev. D 49 (1994) 366; U. Chattopadhyay and P. Nath, Phys. Rev. D 53 (1996) 1648; T. Moroi, Phys. Rev. D 53 (1996) 6565 [Erratum-ibid. D 56 (1996) 4424]; M. Carena, G.F. Giudice and C.E. Wagner, Phys. Lett. B 390 (1997) 234.
 27. J.L. Feng and K.T. Matchev, Phys. Rev. Lett. 86 (2001) 3480.
 28. L.L. Everett, G.L. Kane, S. Rigolin and L.T. Wang, Phys. Rev. Lett. 86 (2001) 3484; U. Chattopadhyay and P. Nath, Phys. Rev. Lett. 86 (2001) 5854; S. Komine, T. Moroi and M. Yamaguchi, Phys. Lett. B 506 (2001) 93.
 29. The LEP Higgs working group, hep-ex/0107030, <http://lephiggs.web.cern.ch/LEPHIGGS/>.
 30. M. Dine, A. Kagan and S. Samuel, Phys. Lett. B 243, (1990) 250; S. Dimopoulos and G.F. Giudice, Phys. Lett. B 357 (1995) 573; A. Pomarol and D. Tommasini, Nucl. Phys. B 466 (1996) 3; A.G. Cohen, D.B. Kaplan and A.E. Nelson, Phys. Lett. B 388 (1996) 588; J. Hisano, K. Kurosawa and Y. Nomura, Phys. Lett. B 445 (1999) 316; Nucl. Phys. B 584 (2000) 3.
 31. G.C. Cho, N. Haba and J. Hisano, Phys. Lett. B 529 (2002) 117.
 32. L.J. Randall and R. Sundrum, Nucl. Phys. B 557 (1999) 79; G.F. Giudice, M.A. Luty, H. Murayama and R. Rattazzi, JHEP 9812 (1998) 027.
 33. H. Baer and J. Ferrandis, Phys. Rev. Lett. 87 (2001) 211803.
 34. J. Hisano and K. Tobe, Phys. Lett. B 510 (2001) 197.
 35. E.A. Baltz and P. Gondolo, Phys. Rev. Lett. 86 (2001) 5004.
 36. K. Abe *et al.* [BELLE Collaboration], BELLE-CONF-0118.
 37. T. Ohshima, talk at the workshop "Neutrino oscillations and their origin" (NOON2001) (ICRR, Univ. of Tokyo, Kashiwa, Japan, Dec., 2001).
 38. M.L. Brooks *et al.* [MEGA Collaboration], Phys. Rev. Lett. 83 (1999) 1521.
 39. L.M. Barkov *et al.*, Research Proposal for experiment at PSI (1999).
 40. J. Äystö *et al.*, "Physics with Low-Energy Muons at a Neutrino Factory Complex", hep-ph/0109217.
 41. D.E. Groom *et al.* [Particle Data Group Collaboration], Eur. Phys. J. C 15 (2000) 1.
 42. P. Wintz, in Proceeding of the International Symposium "Lepton and Baryon Number Violation", (eds. H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Institute of Physics

- Bristol, 1998), p.534.
43. SINDRUM II Collaboration, Research Proposal for experiment at PSI (1999).
 44. M. Bachmann *et al.* [MECO Collaboration], Research Proposal E940 for experiment at BNL (1997).
 45. Y. Kuno and Y. Okada, Rev. Mod. Phys. 73 (2001) 151; M. Furusaka *et al.*, JAERI/KEK Joint Project Proposal “The Joint Project for High-Intensity Proton Accelerators”, KEK-REPORT-99-4, JAERI-TECH-99-056.
 46. A. Czarnecki, W.J. Marciano and K. Melnikov, hep-ph/9801218; R. Kitano, M. Koike and Y. Okada, hep-ph/0203110.
 47. R. Barbieri, S. Ferrara and C.A. Savoy, Phys. Lett. B 119 (1982) 343; R. Arno v it t, P. Nath and A.H. Chamseddine, Phys. Rev. Lett. 49 (1982) 970; L.J. Hall, J. Lykken and S. Weinberg, Phys. Rev. D 27 (1983) 2359.
 48. M. Dine and A.E. Nelson, Phys. Rev. D 48 (1993) 1277; M. Dine, A.E. Nelson and Y. Shirman, Phys. Rev. D 51 (1995) 1362; M. Dine, A.E. Nelson, Y. Nir and Y. Shirman, Phys. Rev. D 53 (1996) 2658; G.F. Giudice and R. Rattazzi, Phys. Rept. 322 (1999) 419.
 49. D.E. Kaplan, G.D. Kribs and M. Schmaltz, Phys. Rev. D 62 (2000) 035010; Z. Chacko, M.A. Luty, A.E. Nelson and E. Ponton, JHEP 0001 (2000) 003; M. Schmaltz and W. Skiba, Phys. Rev. D 62 (2000) 095005.
 50. L.J. Hall, V.A. Kostelecky and S. Raby, Nucl. Phys. B 267 (1986) 415; R. Barbieri and L.J. Hall, Phys. Lett. B 338 (1994) 212; J. Hisano, T. Moroi, K. Tobe, and M. Yamaguchi, Phys. Lett. B 391 (1997) 341; [Erratum-ibid. B 397 (1997) 357].
 51. R. Barbieri, L. Hall, and A. Strumia, Nucl. Phys. B 445 (1995) 219; P. Ciafaloni, A. Romanino and A. Strumia, Nucl. Phys. B 458 (1996) 3; N. Arkani-Hamed, H.C. Cheng, and L.J. Hall, Phys. Rev. D 53 (1996) 413 J. Hisano, D. Nomura, Y. Okada, Y. Shimizu and M. Tanaka, Phys. Rev. D 58 (1998) 116010; A. Romanino and A. Strumia, Nucl. Phys. B 622 (2002) 73.
 52. F. Borzumati and A. Masiero, Phys. Rev. Lett. 57 (1986) 961; J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi and T. Yanagida, Phys. Lett. B 357 (1995) 579; J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Rev. D 53 (1996) 2442; J. Hisano and D. Nomura, Phys. Rev. D 59 (1999) 116005; W. Buchmüller, D. Delepine and F. Vissani, Phys. Lett. B 459 (1999) 171; M.E. Gomez, G.K. Leontaris, S. Lola and J.D. Vergados, Phys. Rev. D 59 (1999) 116009; J.R. Ellis, M.E. Gomez, G.K. Leontaris, S. Lola and D.V. Nanopoulos, Eur. Phys. J. C 14 (2000) 319; W. Buchmüller, D. Delepine and L.T. Handoko, Nucl. Phys. B 576 (2000) 445; J.L. Feng, Y. Nir and Y. Shadmi, Phys. Rev. D 61 (2000) 113005; J. Sato and K. Tobe, Phys. Rev. D 63 (2001) 116010; D. Carvalho, J. Ellis, M. Gomez and S. Lola, Phys. Lett. B 515 (2001) 323.
 53. J.L. Feng and T. Moroi, Phys. Rev. D 61 (2000) 095004.
 54. N. Arkani-Hamed, H.-C. Cheng, J.L. Feng, and L.J. Hall, Phys. Rev. Lett. 77 (1996) 1937; Nucl. Phys. B505 (1997) 7; N.V. Krasnikov, Phys. Lett. B 388 (1996) 783; M. Hirouchi and M. Tanaka, Phys. Rev. D 58 (1998) 032004; J. Hisano, M.M. Nojiri, Y. Shimizu and M. Tanaka, Phys. Rev. D 60 (1999) 055008; J. Hisano, hep-ph/9906312; K. Agashe and M. Graesser, Phys. Rev. D 61 (2000) 075008; D. Nomura, Phys. Rev. D 64 (2001) 075001; I. Hinchliffe and F.E. Paige, Phys. Rev. D 63 (2001) 115006; J. Hisano, R. Kitano and M.M. Nojiri, hep-ph/0202129.
 55. B.C. Regan, E.D. Commins, C.J. Schmidt and D. DeMille, Phys. Rev. Lett. 88 (2002) 071805.
 56. S.K. Lamoreaux, nucl-ex/0109014.
 57. H.N. Brown *et al.* [Muon g-2 Collaboration], Phys. Rev. Lett. 86 (2001) 2227.
 58. Y.K. Semertzidis *et al.*, hep-ph/0012087.
 59. J.R. Ellis, J. Hisano, M. Raidal and Y. Shimizu, Phys. Lett. B 528 (2002) 86.
 60. J. Hisano, D. Nomura and T. Yanagida, Phys. Lett. B 437 (1998) 351.
 61. Y. Okada, K. Okumura and Y. Shimizu, Phys. Rev. D 58 (1998) 051901; Phys. Rev. D 61 (2000) 094001.
 62. J.R. Ellis, J. Hisano, M. Raidal and Y. Shimizu, Phys. Lett. B 528 (2002) 86.